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Resource Efficient Process Chain Development of a Modular CubeSat Spaceframe

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Abstract

A CubeSat is a 10×10×10 cm cube that can weigh up to 1.33 kg. This design offers a less expensive alternative for space enthusiasts to explore the cosmos, even though the total weight is very limited. For a CubeSat to be allowed to launch, it must adhere to certain specifications outlined in the CubeSat Design Specifications document. This places several restrictions on the satellite in terms of weight, size and center of gravity, and innovative solutions need to be explored during integration to meet these specifications. Having a spaceframe that can easily be assembled and disassembled will help smooth out the integration stage and save a significant time that can then be allocated elsewhere in the developmental stages. The increasing relevance of resource efficient manufacturing is prevalent through the continually rising costs of resources and energy. In order to stay competitive, manufacturers must develop resource efficient process chains to gain an advantage in the market. This study focused on developing a resource efficient process chain to manufacture a modular CubeSat spaceframe. This spaceframe must adhere to the CubeSat Design specifications, as well as meet the customer's needs. A unique assembly process was designed that eliminated the need for screws structure together. Instead the spaceframe relies on interference fits, and utilizes the unique deployment method of the Poly-Picosatellite Orbital Deployer to ensure that the assembly does not fail. A material selection procedure was utilized, along with resource efficient manufacturing process chains to develop a CubeSat structure that is very cost effective to produce, easily assembled and disassembled and weighed less than most of the market leading CubeSat structures.

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1. Introduction

Stanford University's Department of Aeronautics and Astronautics established the Space Systems Development Laboratory (SSDL) in 1994 with the purpose of providing project-based learning programs for engineering students [1]. The goal of this program is for students to gain experience in systems engineering and was designed to take the students through the life cycle of a project. In this case, the project was the design, development, fabrication, testing, launch integration and space operations of a microsatellite. The CubeSat program was initially conceptualized as a tool to not only help teach students about the process involved in the development of a spacecraft, but the launching and operational processes as well [2]. The driving force behind the idea was to create a small and inexpensive standardized satellite design to support a wide variety of demonstration applications while having a much shorter development cycle [3]. The accelerated schedule of the CubeSat program allows students to be involved in the complete life cycle of a satellite, including mission requirements and planning; design, analysis and testing; fabrication, assembly and quality control; system level testing; integration and launch and ground-based satellite operations [4].

The use of the CubeSat platform to carry out missions in space have greatly increased over the last decade, when compared to other satellite classes. This surge in growth is supported by massive advancement in the technologies used by these small satellites. This environment is an excellent incubator for innovation, which in turn promotes a steady growth in the industry. The biggest limiting factor of the CubeSat platform is the weight restriction of the final satellite, which can force the designers to either compromise on certain aspects of the design, or move the satellite into a different class. Although the advancement of the technologies used by the satellites are big, the same innovation is not shared when it comes to spaceframe development. Several companies have brought a good product to market, but never improved on the design when it was successful.

This study aims to develop a process chain for manufacturing a CubeSat spaceframe. The core principles of resource efficiency will be used to gain a competitive edge over products in the market and establish a viable product for use.

2. The value stream perspective

In-depth optimization of individual production processes, with specific emphasis on quality, reliability and output, are vital factors for sustainable success, however it is not always enough to defy competition. Improvements of individual production processes can easily get lost in the bigger picture if not planned and implemented with reference to the entire production process. The main difference between the traditional supply chain and the value stream is that the supply chain includes the complete list of activities of all the stakeholders involved, whereas the value stream is only concerned with the specific processes that adds value to the end consumer [5]. The value stream perspective considers the correlation between various individual production- and business processes, material and information flow, and the customer and supplier to provide a holistic view which will enable an improvement of the entire production procedure [6]. Figure 1 is an example of a value stream in a factory where each of the six basic elements interact with each other to form the bigger picture of the production process. The entire production process for manufacturing the CubeSat spaceframe was mapped out in Figure 1 and ensured that the improvements of the individual production processes did not get lost in the bigger picture.

The six basic elements seen in Figure 1 is described as follows:

1. The *production process* not only encompasses all of the production processes within the factory, but all of the external processing activities as well. This involves modelling each product within the entire process range as an individual production procedure, focusing only on the production process level and leaving aside the resource-related aspects, with the aim of outlining the differences between the various production procedures.

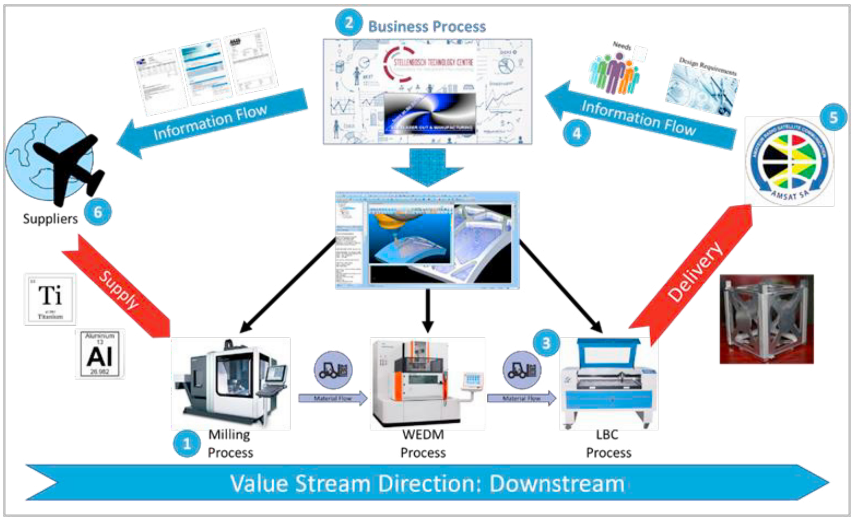

Figure 1: Value stream in a factory (Adapted from [6])

2. The *business processes* generate, process and store all the information required during production planning and control to complete a customer's order. The mapping of business processes during value stream design is not explicitly aimed towards a detailed systematic representation of the entire work process, but rather a clear, well-arranged depiction of the overall procedure.

3. The movement of materials between production processes is defined as *material flow*. Within the value stream, material flow consists of three components: transport, handling and storage. The temporary placement of materials, products or parts is described by storage. This usually occurs within an appropriate storage facility. Transport is the moving of materials, products and/or parts to their respective retrieval areas, while handling describes the manual activities required in stockpiling and removal of stock. The production processes are logistically linked by material flow.

4. *Information flow* not only includes the transmission of data and documents between business- and production processes but also between individual business processes. The business processes are connected by the information flow in a similar manner as the production processes are linked to each other by the material flow. In addition to this, information is also passed on from business processes to production processes, controlling everything from production scheduling to the appropriate material flows.

5. *The customer* depicts the demand that needs to be met by the production process. Value stream design aims at customer-oriented production, which means that the customer is the first element to be observed after the production process.

6. The production system's supply of raw materials is intuitively represented by *the supplier*.

The customer information that feeds the business process include the needs statement and design requirements. This information is then filtered into material selection, product design and process selection, which then moves on to the respective entities. Information flow to the suppliers include the necessary material specifications, while the design and manufacturing data is processed by various CAD/CAM programs to produce the optimal manufacturing solution. The resource efficient process chains developed for each of the manufacturing processes ensured that all of the information culminated into the maximum value added to the customer.

3. Resource efficient manufacturing

Modern life is highly dependent on the limited supply of natural resources, with demand rapidly increasing due to emerging economies of developing countries [7]. This section explores the concept of resource efficiency during manufacturing with the end goal of reducing the dependency on natural resources through the 6R-based material flow and product and production optimization.

3.1. Evolution of production systems

The manufacturing industry has undergone many revolutionary changes over the years, yet it remains as the backbone of a modern industrialized society and has cemented itself as the cornerstone of the world's economy. These changes in the manufacturing paradigms can be attributed to changes in market and social imperatives, and the development of new and enabling technologies [8]. Figure 2 illustrates the above-mentioned paradigm shifts in terms of product volume, product variety and increasing degree of complexity.

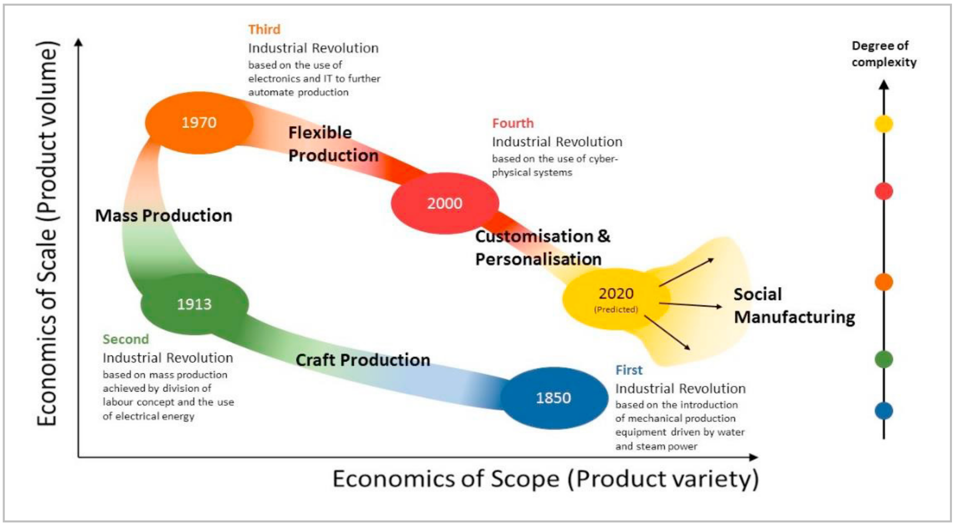

Figure 2: Evolution of manufacturing paradigms [8].

The first industrial revolution enabled craft production to focus more on economics of scale, and was supported by the invention of assembly lines. With specific products saturating the market in the 1970's, society demanded greater product variety, which lead the industry to move into an era of customization and personalization. Since the fourth industrial revolution the customers' needs has shifted from mass produced products, to high-tech, personalized, consumer driven items. These complex processes of product variability and shortened product life cycles requires an in-depth knowledge of consumer preferences and open communication to the customers and suppliers.

Industry 4.0 is the fourth industrial revolution, which will enable companies to have machines, that communicate with each other to manufacture products. There is a continuous desire to improve quality of manufacturing and industry has been significantly developing to provide the high level of production. Unfortunately, the manufacturing processes implemented currently lack sustainability. Production contributes to climate change as well as the depletion of natural resources. This creates a need in industry for sustainable production solutions through the implementation of resource efficient manufacturing practices.

3.2. Goals of production

The primary objectives of a production process have always been to reduce the cost, improve the quality and shorten the lead-time. If we consider the most recent paradigm shift, as described in Figure 2, we can add variability as the fourth goal dimension of production. Figure 3 below illustrates the four goal dimensions through which the efficiency of production can be increased. Each goal dimension comprises of several partial goals, which in their reciprocal correlations define a production's system of goals and accordingly also the factory goals [6]:

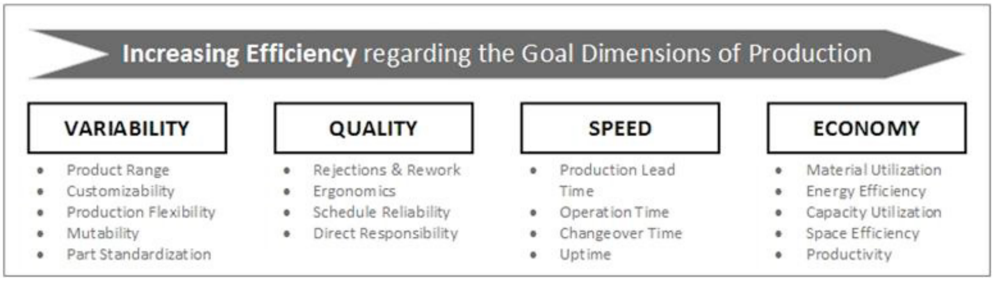

Figure 3: Primary objectives of a production process

The variability of production is an indication of how wide the attainable production range is. This dimension indicates how many variants of a certain product will be produced and whether customized products are available. Having a highly flexible production system will ensure that short term variations in market demand is met, while mutability will enable production to respond to product requirements changing in the short to medium term. The quality of production indicates the reliability of any of the production processes, and how well the tolerance levels are complied with. The speed of production is a good indication of how time-consuming the value-adding steps of production are. Finally, the productivity is indicated by the economy of production. This considers all the production cost factors that are influenced by the requirements of variability, quality and speed. Intuitively, by increasing the efficiency of each of the above-mentioned goals, the overall efficiency of the entire process will be increased. This, however, is not true since the four goal dimensions conflict with each other. These goal conflicts are severe, with some goals more easily achievable than others, some goals being compatible to some extent, and the attainment of certain goals are completely incompatible [6]. Figure 4 depicts the four goal dimensions arranged in a square, with the conflicting relationships between each goal dimension indicated by the four sides and the two diagonal lines of the square.

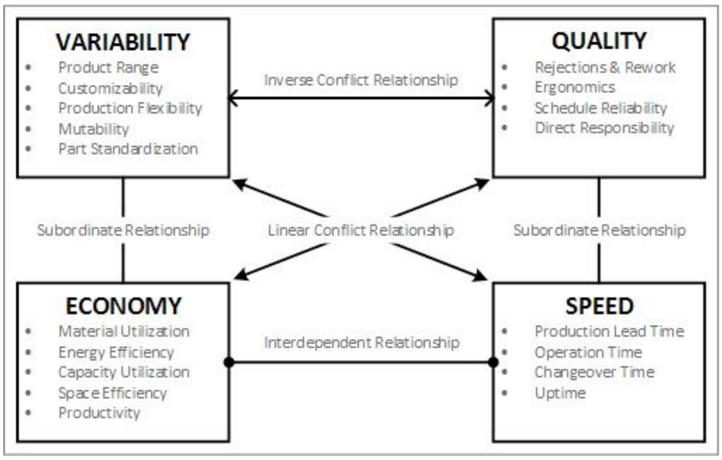

Figure 4: Interaction of primary objectives of a production process

The conflict line between Quality and Economy suggest that an improvement in quality will increase the production costs. If one focusses to increase the quality of a product, then you require more precise and expensive equipment, highly skilled, therefore better payed, workers to operate the machinery and additional quality assurance processes. Refraining from these additional expenses will lead to an increase in product defects, as fewer parts will fall within the higher quality requirements. Finding a balance where adequate quality is achieved while still producing an economically competitive product is a key aspect of increasing the production efficiency.

The goals of trying to increase variability while trying to decrease speed is contradicting since an increase in variability will lead to longer delivery times and/or higher inventory levels. The shortest possible delivery time can be achieved by holding all the products on stock, since it is faster to withdraw stock than to manufacture the product. By limiting the variability of a product, one can increase the delivery speed and decrease the manufacturing time, but this will limit the number of customers as consumers are moving towards mass customization and personalization of products [9]. A solution to this dilemma could exist in providing a consumer with a sense of customization, where they can specify certain requirements while in fact keeping the product variability to a minimum. This concept will be explored further later in the study.

The conflict line between variability and quality is an indication that with an increased variability, it would be more difficult to meet the quality goals, and on the other hand, an increase in quality requirements would restrict variety and flexibility. A new type of risk associated with unplanned delays during production is brought about by an increase in product variety due to customer specific design adaptations. Quality problems due to slow or incorrect design adaptations can be eliminated by having a customer select a product from a catalogue, but this will in turn limit the variability or greatly increase the inventory cost if a very large product catalogue is available.

In most cases, it is easier to improve productivity and utilization, as indicated by the conflict line between variability and economy. It is generally easier to reduce the manufacturing cost of a standard product than to make an existing production system more flexible in order to manufacture a more diverse product range. Increasing the adaptability of an existing production system is a challenging undertaking since it requires changing the design of the existing manufacturing resources, even though a more flexible machine can be better utilized than an inflexible one. It is possible to fulfil both goal dimensions, even though they are located on completely different levels of production design. They still conflict with each other, as too much flexibility will decrease the overall production efficiency.

It is much easier to decrease the manufacturing- or delivery time of a production process than to increase the standards to which a product must adhere, as indicated by the conflict line between the speed and quality goal dimensions. By developing a good strategy to manage the manufacturing process, it is possible to improve production reliability by reducing the manufacturing lead-time. Similarly, the quality of some production processes will rise, if execution is accelerated.

Finally, the conflict line between economy and speed is an indication that both goal dimensions can be improved at the same time. By reducing the setup times in conjunction with smaller lot sizes will result in decreased inventories, reduced lead times, an increase in machine utilization and lower setup costs. Decreasing lead-time inevitably reduces the associated inventory costs, thus to some extent indicating that both economy and speed correlate positively to one another.

An optimal solution would then be to develop a process chain with emphasis on quality, rather than variability. The increased production costs that results from focusing on quality can be countered by standardizing the components. This will decrease the manufacturing time, increase the delivery speed of the product, and minimize the inventory needed for a flexible production system.

3.3. 6R's for sustainable manufacturing

Sustainable manufacturing can be defined as the creation of products that utilizes processes that [10]:

- Minimize negative environmental impacts
- Conserve energy and natural resources
- Are safe for employees, communities and consumers

- Are economically sound

Finding a solution to the issues of sustainable manufacturing, involves viewing it as a complex systems problem with three integral interacting levels: products, processes and systems [11]. Figure 5 is a visual representation of this systems problem where the interaction between the levels to achieve sustainable manufacturing.

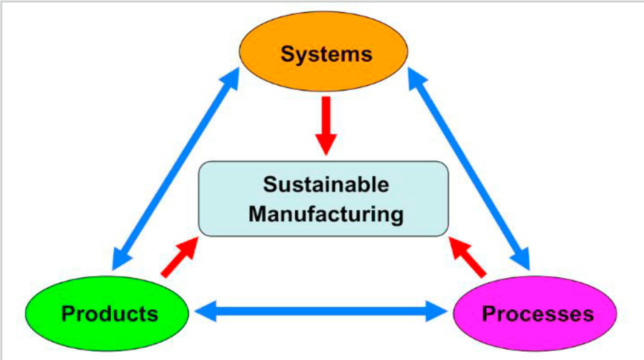

Figure 5: Integrated elements of sustainable manufacturing ([11])

The principles of 3R's: *Reduce, Reuse and Recycle,* is the foundation on which green manufacturing is based [12]. These principles were derived from lean manufacturing practices, which focused on the elimination of waste throughout the entire process, and lean manufacturing is in turn based on 1R (Reduce) which was introduced in the 1980's [11]. The interaction between each of these manufacturing principles, as well as the approximate stakeholder value can be seen in Figure 6. The current trend for achieving sustainable value in manufacturing requires the transformation from lean manufacturing, to green manufacturing, to sustainable manufacturing.

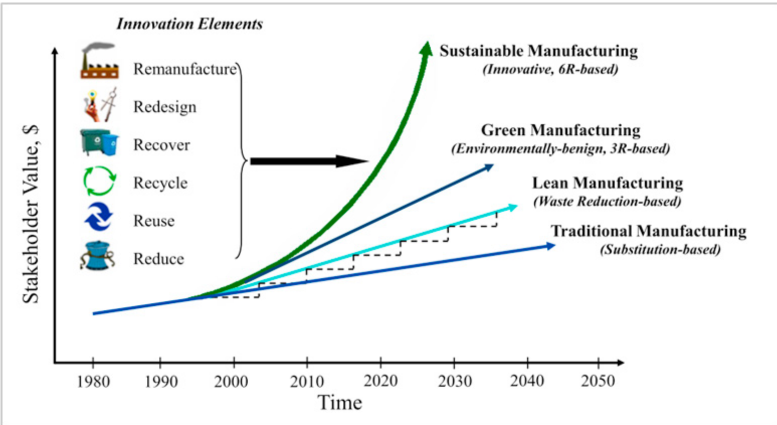

Figure 6: The six basic elements seen in Figure 1 is described as follows:

The interaction between the manufacturing process chain and the 6R principles have a positive influence on the environment, as it enables a near-perpetual material flow while facilitating the optimal use of energy, raw materials and other resources [13]. The six principles can be explained as follows [10]:

- ***Reduce*** focusses on the first three stages of the product lifecycle. The reduced use of resources in pre-manufacturing, reduced use of energy, materials and other resources during manufacturing, and reduction of emissions and waste during the *use* stage.
- ***Reuse*** refers to the reuse of either the entire product, or its components, after its first life cycle. The end-goal of this principle is to reduce the usage of virgin materials during production of new products.
- ***Recycle*** is the process of converting material that would otherwise be considered waste into new materials or products.
- ***Recover*** involves the collection of products at the end of the *use* stage, disassembling, sorting and cleaning for utilization in subsequent life cycles.
- ***Redesign*** involves the act of redesigning the next generation of products to use components, materials and resources recovered from previous life cycles.
- ***Remanufacture is*** the process of restoring used products to their original state through the reuse of as many parts as possible

4. Research methodology

The research methodology that was used to complete this study is depicted in Figure 7. It consists of four phases, designed specifically to reach the research objective. The grey diamond shape in the background of the figure not only represents the knowledge gained as the phases progressed, but also the effort required during each of the phases. Phase 1 provided the platform for the study and described the research questions as well as the project objectives. Phase 2 was aimed at bridging the knowledge gap that existed at the start of the study. Focus was placed on resource efficient manufacturing practices to help determine the best practices for resource efficient process chains development. Phase 3 incorporated these results to shape the resource efficient process chains, and Phase 4 validated the design by implementing it in a real-world scenario.

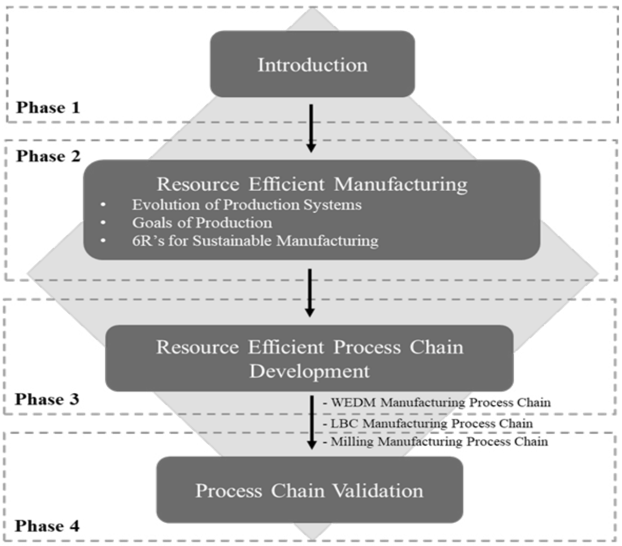

Figure 7: Research methodology process

5. Manufacturing process chain design

5.1. WEDM manufacturing process chain

The WEDM process involves cutting the rails of the CubeSat spaceframe from a 7075-T6 aluminum plate. Figure 8 depicts the primary process chain for the rails. The aluminum plate is clamped in the machine bed with a tolerance of ±0.005 mm to ensure that the resulting part falls within the required part dimensions. Setting up the machine involves importing the 2D wireframe of the profile to be cut. The starting position of the wire is offset 1mm from the edge of the plate. The reason for this starting position is that the WEDM machine needs a flat surface on the part to start the cut. To achieve the required surface roughness, multiple passes needed to be made, resulted to 120 min machine time per part. The inspection process involved making sure that the grooves in the rails which will house the side panels falls within the required tolerances to achieve a sliding fit with interference. Certified gauge blocks were used to check for a go/no-go tolerance. The post processing of the rails ensures that their length correlates to the design specifications and was micro-milled to within ±0.05 mm, which is well within the required tolerance range.

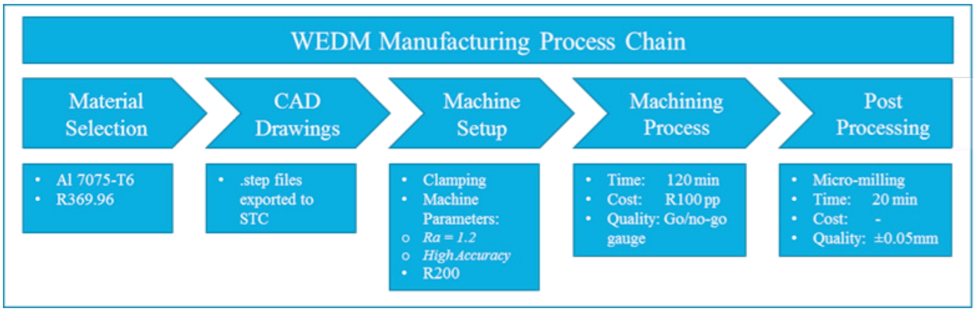

Figure 8: Resource efficient WEDM process chain to manufacture the CubeSat rails

5.2. LBC manufacturing process chain

The process chain for the Laser Beam Cutting process can be seen in Figure 9 below. Because the laser cutting process is a two-dimensional process, it required a wireframe format of the top view of the part to be cut. The CAD file was exported as a STEP file and uploaded to the machine. The correct material was loaded onto the cutting bed after which the manufacturing process was initiated. Because the laser cutting process was outsourced to a local manufacturing company, the exact time of manufacture could not be measured as the CubeSat components formed part of a batch operation in which multiple components for various customers are manufactured in one job.

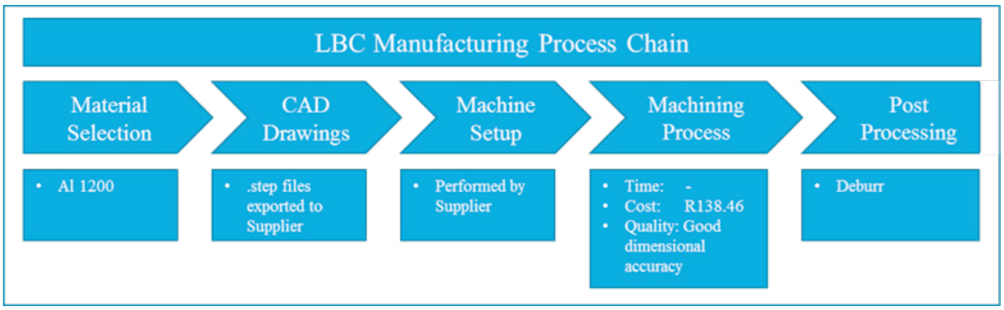

Figure 9: Resource efficient LBC process chain to manufacture the CubeSat top, bottom and side panels

The deburring process was necessary to remove the rough edges from the panels after laser cutting. All the edges of the part in question was manually smoothed out using a deburring tool and each panel has been visually inspected to ensure that all the edges are smoothed out.

5.3. Milling manufacturing process chain

Figure 10 illustrates the resource efficient process chain that was used to manufacture the CubeSat standoffs. The CubeSat standoffs are milled from a 9 mm x 9 mm x 15 mm block of 7075-T6 Aluminum. Each CubeSat spaceframe has eight standoffs, four on top, and four on the bottom. The purpose of the standoffs is to ensure separation between the CubeSats in the P-POD by minimizing the surface contact between each satellite. The specialized clamping method that held the workpiece to the machine bed ensured repeatability of the process while greatly decreasing the setup time. Once the zero point was established, the chamfer of the standoff was cut, after which the workpiece is turned upside down to mill the top profile, which is needed for assembly. The top profile is a key feature of the standoff that integrates precisely with the rails to hold the spaceframe together. The quality control of the standoffs was made to ensures that each part falls within the specific design requirements. This strict QC process is in place because the standoffs not only protect the payload of the CubeSat, but also ensure the safety of all the CubeSats in the P-POD by providing adequate separation and minimal surface contact.

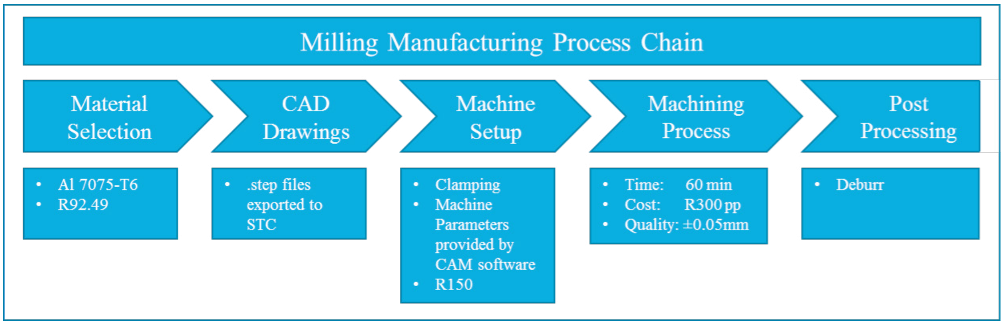

Figure 10: Resource process chain used for manufacturing the CubeSat

A time-cost breakdown for the CubeSat spaceframe can be seen in Table 1. The Total manufacturing time for the spaceframe adds up to 1020 minutes, and the total cost can be rounded to R3600. The lengthy manufacturing time was due to the trade-off made for the accuracy that was achieved during manufacturing. By improving the resource efficiency of the process chains, the manufacturing cost severely reduced when compared to previous iterations.

Table 1: Time-cost breakdown for the CubeSat spaceframe

		Time (min)			**Cost (Rand)**					
Component	**Number**	**Setup**	**Machine**	***Total***	**Setup**	**Machine**	**Material**	***Total***	**Weight (grams)**	**Quality**
Standoff	8.00	15.00	45.00	*480.00*	150.00	300.00	46.23	*2 596.23*	-	0.05
Rail	4.00	30.00	120.00	*510.00*	200.00	100.00	92.49	*692.49*	-	0.0013
Top panel	2.00	5.00	10.00	*15.00*	0.00	29.69	0.00	*59.38*	-	0.2
Side panel	4.00	5.00	10.00	*15.00*	0.00	19.77	171.40	*250.48*	-	0.2
Total	**18.00**	**55.00**	**185.00**	***1 020.00***	**350.00**	**449.46**	**310.12**	***3 598.58***	**134**	**0.4513**

6. Conclusion

Future technological advancements will ensure that the miniaturization of components continues to satisfy the market trends regarding small satellites. The reduced weight of these satellites inevitably lowers the launch cost, while at the same time surpassing the capabilities of satellites that once weighed upwards of 1000 kg. With the developments of launch opportunities, especially for small satellites, the market segment is expected to maintain a steady growth deep into the future.

The resource efficient process chains of the CubeSat spaceframe utilize both traditional and non-traditional machining methods to manufacture the components. This allowed for increased flexibility in the manufacturing system while at the same time producing high quality and accurate components. The value stream design follows each process that adds value to the customer, and in doing so, prevents tunnel vision by never losing sight of the bigger picture. Figure 11 shows the cost, weight and design efficiency value of the prototype developed, and the evident that it can provide future customers with a superior CubeSat spaceframe.

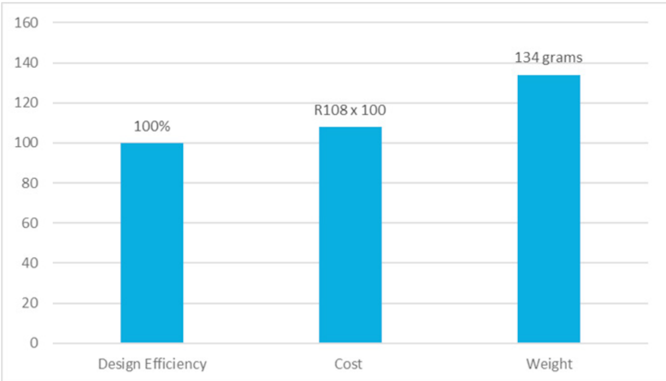

Figure 11: Design Efficiency, Cost and Weight of the KletsKOUS-3 CubeSat spaceframe prototype

Even with a markup of three times the cost price, the spaceframe costs only R10800, which is still only half the price compared to the closest competitor, and with a structure weight of only 134 grams, it is well below the industry standard of 200 grams. The results, therefore, respond to the need in industry for sustainable production solutions through the implementation of resource efficient manufacturing practice that play an integral role in the delivery of the final product and added a considerable amount of value while being resource conscious.

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